

# A CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS: CUORE, AN UPDATE

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(The CUORE COLLABORATION)

## Abstract

CUORE is a proposed tightly packed array of 1000  $TeO_2$  bolometers, each being a cube 5 cm on a side with a mass of 750 gms. The array consists of 25 vertical towers, arranged in a square, of 5 towers by 5 towers, each containing 10 layers of 4 crystals. The design of the detector is optimized for ultralow- background searches for neutrinoless double beta decay of  $^{130}Te$  (33.8% abundance), cold dark matter, solar axions, and rare nuclear decays. A preliminary experiment involving 20 crystals of various sizes (MIBETA) has been completed, and a single CUORE tower is being constructed as a smaller scale experiment called CUORICINO. The expected performance and sensitivity, based on Monte Carlo simulations and extrapolations of present results, are reported.

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# 1 INTRODUCTION

Neutrinoless double-beta decay, is a process by which two neutrons in a nucleus beta decay by exchanging a virtual Majorana neutrino, and each emitting an electron. This violates lepton number conservation ( $\Delta l = 2$ ) [1]. There are many reviews on the subject [2 - 4].

The decay rate for the process involving the exchange of a Majorana neutrino can be written as follows:

$$\lambda_{\beta\beta}^{0\nu} = G^{0\nu}(E_0, Z) < m_\nu >^2 |M_f^{0\nu} - (g_A/g_V)^2 M_{GT}^{0\nu}|^2. \quad (1)$$

In equation (1)  $G^{0\nu}$  is the two-body phase-space factor including coupling constants,  $M_f^{0\nu}$  and  $M_{GT}^{0\nu}$  are the Fermi and Gamow-Teller nuclear matrix elements respectively, and  $g_A$  and  $g_V$  are the axial-vector and vector relative weak coupling constants, respectively. The quantity  $< m_\nu >$  is the effective Majorana neutrino mass given by:

$$< m_\nu > \equiv \left| \sum_{k=1}^{2n} \lambda_k^{CP} (U_{lk}^L)^2 m_k \right|, \quad (2)$$

where  $\lambda_k^{CP}$  is the  $CP$  eigenvalue associated with the  $k^{th}$  neutrino mass eigenstate ( $\pm 1$  for  $CP$  conservation),  $U_{lk}^L$  is the  $(l, k)$  matrix element of the transformation between flavor eigenstates  $|\nu_l >$  and mass eigenstates  $|\nu_k >$  for left handed neutrinos;

$$|\nu_l > = \sum U_{lk}^L |\nu_k >, \quad (3)$$

and  $m_k$  is the mass of the  $k^{th}$  neutrino mass eigenstate.

The effective Majorana neutrino mass,  $< m_\nu >$ , is directly derivable from the measured half-life of the decay as follows:

$$< m_\nu > = m_e (F_N T_{1/2}^{0\nu})^{-1/2} eV, \quad (4)$$

where  $F_N \equiv G^{0\nu} |M_f^{0\nu} - (g_A/g_V) M_{GT}^{0\nu}|^2$ , and  $m_e$  is the electron mass. This quantity derives from nuclear structure calculations and is model dependent as shown later.

The most sensitive experiments thus far utilize germanium detectors isotopically enriched in  $^{76}Ge$  from 7.78% abundance to  $\sim 86\%$ . This activity began with natural abundance  $Ge$  detectors by Fiorini et al; in Milan [5] evolving over the years to the first experiments with small isotopically enriched  $Ge$  detectors [6], and finally to the two present multi-kilogram isotopically enriched  $^{76}Ge$  experiments: Heidelberg Moscow [7] and IGEX [8]. These experiments have achieved lower bounds on the half-life of the decay  $^{76}Ge \rightarrow ^{76}Se + 2e^-$  :  $T_{1/2}^{0\nu} > 1.9 \times 10^{25}y$  [7] and  $T_{1/2}^{0\nu} > 1.6 \times 10^{25}y$  [8]. Reference [7] has about four times the exposure as reference [8] with data of similar quality. This strongly implies that these experiments with the order of 100 moles of  $^{76}Ge$  each are have reached their point of diminishing returns. Their continuation will yield little more information of fundamental interest. The latest large-space

shell model calculation yields  $F_N = 1.41 \times 10^{-14} y^{-1}$  [9]. This value implies that the above half-lives yield  $\langle m_\nu \rangle \leq 1.0 \text{ eV}$ . Other calculations, discussed later, yield values as small as  $0.3 \text{ eV}$ .

Where should the field of  $\beta\beta$  - decay go from here? Suppose we consider the observed neutrino oscillations in the data from atmospheric neutrinos [10] and solar neutrinos [11]. Considering these data, what probable range of  $\langle m_\nu \rangle$  is implied? Would it be large enough for a direct observation of  $0\nu\beta\beta$  decay? If so, what technique would be the best for a possible discovery experiment? How much would such an experiment cost? We will address these questions in an effort to demonstrate that CUORE, an array of 1000, 750 *gm TeO<sub>2</sub>* bolometers, is the best approach presently available. It can be launched without isotopic enrichment nor extensive R & D, and that it can achieve next generation sensitivity.

## 2 THEORETICAL MOTIVATION: PROBABLE NEUTRINO SCENARIOS

The Superkamiokande data imply maximal mixing of  $\nu_\mu$  with  $\nu_\tau$  with  $\delta m_{23}^2 \simeq 3 \times 10^{-3} \text{ eV}^2$ . The solar neutrino data from SuperK and from SNO also imply that the small mixing angle solution to the solar neutrino problem is disfavored, so that  $\delta m^2$  (solar)  $\simeq (10^{-5} - 10^{-4}) \text{ eV}^2$ . Based on these interpretations, one probable scenario for the neutrino mixing matrix has the following approximate form:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (5)$$

The neutrino masses can be arranged in two hierarchical patterns in which  $\delta m_{31}^2 \simeq \delta m_{32}^2 \sim 3 \times 10^{-3} \text{ eV}^2$ , and  $\delta m_{21}^2 \sim (10^{-5} - 10^{-4}) \text{ eV}^2$ . With the available data, it is not possible to determine which hierarchy,  $m_3 > m_1(m_2)$ , or  $m_1(m_2) > m_3$ , is the correct one, nor do we know the absolute value of any of the mass eigenstates.

The consideration of reactor neutrino and atmospheric neutrino data together strongly implies that the atmospheric neutrino oscillations are very dominantly  $\nu_\mu \rightarrow \nu_\tau$  ( $\nu_\mu \rightarrow \nu_\tau$ ), which implies, as seen from equation [5], that  $\nu_e$  is very dominantly a mixture of  $\nu_1$  and  $\nu_2$ . In this case there will be one relative *CP* phase,  $\epsilon$ , and equation reduces to the approximate form:

$$\langle m_\nu \rangle = \frac{1}{2}(m_1 + \epsilon m_2), \quad (6)$$

where we recall that the large mixing angle solution of the solar neutrino problem implies

$$(m_2^2 - m_1^2) = (10^{-5} - 10^{-4}) \text{ eV}^2. \quad (7)$$

This yields four cases to be analyzed: (a)  $m_1 \simeq 0$ , (b)  $m_1 \gg 0.01 \text{ eV}$ , (c)  $m_3 \simeq 0$ , and (d) the existence of a mass scale,  $M$ , where  $M \gg 0.055 \text{ eV}$ .

- a** If  $m_1 = 0$ ,  $m_2 = (0.003 - 0.01) \text{ eV}$  and  $\langle m_\nu \rangle = \frac{m_2}{2}$ .
- b** If  $m_1 \gg 0.01 \text{ eV} \equiv M$ .  $\langle m_\nu \rangle \simeq \frac{M}{2}(1 + \epsilon) = 0$  or  $M$ .
- c** If  $m_3 = 0$ ,  $m_1 \simeq m_2 \simeq 0.055 \text{ eV}$ .  $\langle m_2 \rangle \simeq 0$  or  $0.055 \text{ eV}$ .
- d** If  $M \gg 0.055 \text{ eV}$ ,  $m_1 \simeq m_2 \simeq M + 0.055 \text{ eV}$ .  $\langle m_\nu \rangle \simeq \frac{m_1}{2}(1 + \epsilon)$ .

If we assume then that  $\epsilon \simeq +1$ , and that neutrinos are Majorana particles, then it is very probable that  $\langle m_\nu \rangle$  lies between  $0.01 \text{ eV}$  and the present bound from  $^{76}\text{Ge}$  experiments.

The requirements for a next generation experiment can easily be deduced by reference to equation (8).

$$T_{1/2}^{0\nu} = \frac{(\ln 2)Nt}{c}, \quad (8)$$

where  $N$  is the number of parent nuclei,  $t$  is the counting time, and  $c$  is the total number of counts, dominantly background. To improve the sensitivity to  $\langle m_\nu \rangle$  by a factor of  $10^{-2}$  from the present  $1 \text{ eV}$  to  $0.01 \text{ eV}$ , one must increase the quantity  $Nt/c$  by a factor of  $10^4$ . The quantity  $N$  can feasibly be increased by a factor of  $\sim 10^2$ , over present experiments so that  $t/c$  must also be improved by that amount. Since the present counting times are probably about a factor of 5 less than a practical counting time, the background should be reduced by a factor of between 10 and 20 below present levels. These are approximately the target parameters of the next generation neutrinoless double-beta decay experiments.

Georgi and Glashow give further motivation for more sensitive next generation double - beta decay experiments [12]. They discuss six "facts" deduced from atmospheric neutrino experiments, and from solar neutrino experiments, and the constraints imposed by the reactor neutrino experiments. They conclude that if neutrinos play an essential role in the large structure of the universe, their six "facts" are "mutually consistent if and only if solar neutrino oscillations are nearly maximal". They further state that stronger bounds on  $0\nu\beta\beta$  - decay could possibly constrain solar neutrino data to allow only the just - so solution.

If, on the other hand, the small angle MSW solution somehow had been the correct one, next generation  $0\nu\beta\beta$  - decay experiments could "exclude the cosmological relevance of relic neutrinos" [12].

### 3 PROPOSED NEXT GENERATION EXPERIMENTS

There are six large volume experimental proposals in various stages of development. CUORE will be discussed in detail later. The remaining five in alphabetical order are: CAMEO, EXO, GENIUS, MAJORANA, and MOON.

The *CAMEO* proposal would place enriched parent isotopes in and near the center of the BOREXINO detector and Counting Test Facility (*CTF*) [13].

The proposed *EXO* detector would be either a large high pressure  $^{136}\text{Xe}$  gas Time Projection Chamber ( TPC ) or a liquid TPC. It would contain tons of  $\text{Xe}$  isotopically enriched in  $^{136}\text{Xe}$  [14].

The *GENIUS* proposal involves between 1 and 10 *tons* of "naked" germanium detectors, isotopically enriched to 86% in  $^{76}\text{Ge}$ , directly submerged in a large tank of liquid nitrogen as a "clean" shield [15].

The *Majorana* proposal is a significant expansion of the IGEX experiment with new segmented detectors, in a highly dense - packed configuration and new pulse shape discrimination techniques developed by PNNL and USC. The proposal involves the production of 250, 2 *kg* isotopically enriched (86%)  $\text{Ge}$  detectors, each segmented into 12 electrically independent segments.

The Molybdenum Observatory of Neutrinos ( MOON ) proposal is a major extension of the ELEGANTS detector. It involves between 1 and 3 tons of molybdenum foils isotopically enriched to 85% in  $^{100}\text{Mo}$  inserted between plastic scintillators.

All of these experiments will require significant time, R & D, and funding for isotopic enrichment as well as the development of new techniques. The CUORE experiment on the other hand requires no isotopic enrichment because the natural abundance of  $^{130}\text{Te}$  is  $(33.80 \pm 0.01)\%$ , and the technique has already been developed. A preliminary experiment, MIBETA, has already been completed [17]. In addition, a preliminary trial experiment, CUORICINO, is being constructed at this time [18]. It is one of the 25 towers of 40 of the 1000, 750 *gm*  $\text{TeO}_2$  bolometers, which is a slight change in the configuration initially designed [18]. CUORICINO will contain 8.11 *kg* of  $^{130}\text{Te}$ . The most conservative nuclear structure calculations imply that  $^{130}\text{Te}$  is 2 times more effective in  $< m_\nu >$  sensitivity than  $^{76}\text{Ge}$ , so that CUORICINO will be equal to at least 16.22 *kg* of  $\text{Ge}$  enriched to 86% in  $^{76}\text{Ge}$ . CUORE would be equivalent to 407 *kg* of 86%  $^{76}\text{Ge}$  with the most conservative nuclear matrix elements or 957 *kg* of 86%  $^{76}\text{Ge}$  according to the largest theoretical matrix elements. There are five nuclear structure calculations presented in Table 1 below [19 - 23].

TABLE 1: Theoretical values of  $F_N$  for the double-beta decay of  $^{76}\text{Ge}$  and  $^{130}\text{Te}$  computed with five nuclear models.

$^{76}\text{Ge}$	$^{130}\text{Te}$				
$F_N(\text{years})^{-1}$	$F_N(\text{years})^{-1}$	$R(t)^+$	$R(\epsilon)^*$	model	Ref.
$1.54 \times 10^{-13}$	$1.63 \times 10^{-12}$	10.6	3.3	Shell Model	[19]
$1.14 \times 10^{-13}$	$1.08 \times 10^{-12}$	9.6	3.1	Generalized Seniority	[20]
$1.86 \times 10^{-14}$	$3.96 \times 10^{-13}$	21.8	4.7	QRPA	[21]
$1.24 \times 10^{-13}$	$4.98 \times 10^{-13}$	3.9	2.0	QRPA	[22]
$1.14 \times 10^{-13}$	$5.33 \times 10^{-13}$	4.7	2.2	QRPA	[23]

<sup>+</sup>  $R(t)$  the ratio of  $F_N(^{130}\text{Te})/F_N(^{76}\text{Ge})$ .

<sup>\*</sup>  $R(\epsilon)$  The ratio  $\sqrt{R(t)}$ ; the relative sensitivity to  $< m_\nu >$  of  $^{130}\text{Te}$  to that of

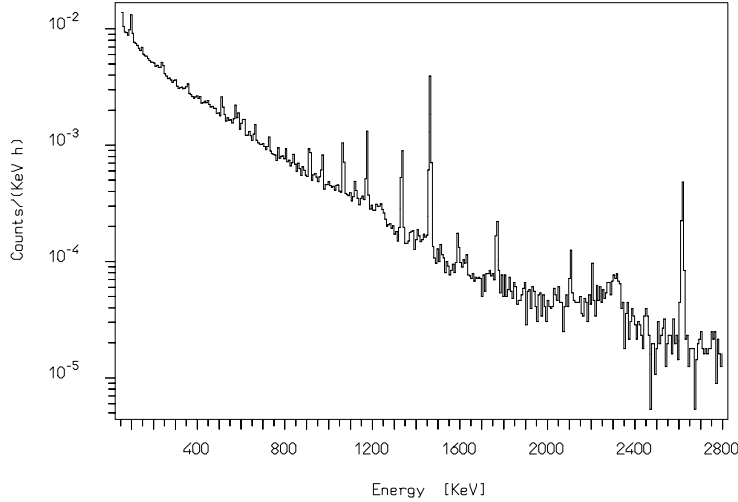


Figure 1: *Final spectrum of the MIBETA experiment.*

$^{76}\text{Ge}$ .

The results of the preliminary experiment MIBETA reported by the Milano - INFN group [17] involved 20 natural  $\text{TeO}_2$  crystal bolometers averaging 340 gm each for a total mass of 6.8 kg. This is equivalent to 1.84 kg of  $^{130}\text{Te}$ . The array was run in a number of configurations with various detectors operating at any one time as the array was used for development of the technique. These experiments ran over a total of 80613 hrs of operation but with several detector configurations. The total exposure was  $Nt = 4.31 \times 10^{24} \text{ y}$  with a bound on the number of counts in the  $0\nu\beta\beta$  - decay region of  $6.9^{+6.7}_{-5.9}$  for an upper bound to 90%  $CL$  of 17.96. The most recent bound on the half - life is  $T_{1/2}^{0\nu} > 1.6 \times 10^{23} \text{ y}$ . This corresponds to the following upper bounds on  $\langle m_\nu \rangle$  for eight nuclear structure calculations: 1.1eV [3], 2.1eV [21], 1.5eV [20], 1.8 eV [23], 2.4 eV [24], 1.9 eV [25], 2.6 eV [26], and 1.5 eV [27]. The range is from 1.1 to 2.6 eV, not much larger than the conservative result from the  $^{76}\text{Ge}$  experiments [7, 8].

The average background for this experiment was 0.5counts/kg/keV/y; however, it was discovered later that the crystals were polished with cerium oxide which was measured in the Gran Sasso Laboratory and found to be radioactive. In addition there is clear evidence of neutron induced background. We have conservatively estimated that the background can be reduced by a factor of at least 10 in CUORICINO. The goal will be to reduce the background significantly below this level, by a factor of 40 or even more.

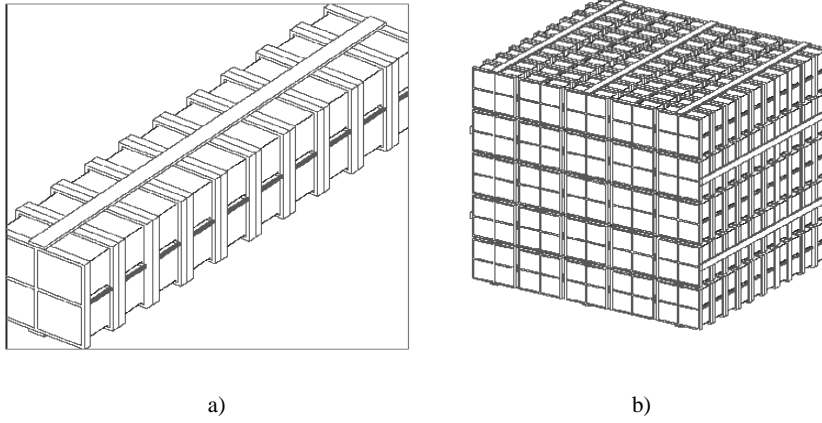


Figure 2: a) A single tower of CUORE; b) The CUORE detector.

TABLE 2: Projected sensitivities of CUORICINO depending on energy resolution and background.

BKG (c/keV kg y)	FWHM = 5 keV		FWHM = 2 keV	
	$\tau_{1/2}(y)$	$\langle m_\nu \rangle (eV)$	$\tau_{1/2}(y)$	$\langle m_\nu \rangle (eV)$
0.5	$3.6 \times 10^{24} \times t^{1/2}$	$0.38 \times t^{-1/4}$	$5.7 \times 10^{24} \times t^{1/2}$	$0.30 \times t^{-1/4}$
0.1	$8.1 \times 10^{24} \times t^{1/2}$	$0.25 \times t^{-1/4}$	$1.3 \times 10^{25} \times t^{1/2}$	$0.20 \times t^{-1/4}$
0.01	$2.6 \times 10^{25} \times t^{1/2}$	$0.14 \times t^{-1/4}$	$2.9 \times 10^{25} \times t^{1/2}$	$0.14 \times t^{-1/4}$

The final spectrum of the MIBETA 20 crystal experiment reported in reference [17] is shown in Figure 1. While improvements are being made at present in the background as well as in the energy resolution, it is clear that this technology has been clearly demonstrated by the results of the MIBETA experiment, and will be further demonstrated by the CUORICINO experiment being constructed at this time.

## 4 THE CUORE DETECTOR

The CUORE will consist of an array of 1000  $TeO_2$  bolometers arranged in a square configuration of 25 towers of 40 crystal each. The geometry of a single tower is shown in Figure 2a. A sketch of CUORE is shown in Figure 2b.

The principle of operation of these bolometers is now well understood [28]. Tellurium Oxide is a dielectric and diamagnetic crystal, which when maintained at very low temperature ( $\sim 5 - 10^\circ \text{millikelvin}$ ) has a very low heat capacity. In fact the specific heat is proportional to the ratio  $(T/T_0)^3$  where  $T_0$  is the

Debye temperature. Accordingly, a very small energy absorbed by the crystal by a nuclear decay or recoil by collision, can result in a measurable increase in temperature. This temperature change can be recorded using Neutron Transmutation Doped (NTD) germanium thermistors. These devices were developed and produced by Haller at the Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley Department of Material Science. These sensors have been made unique in their uniformity of response and sensitivity by neutron exposure control with neutron absorbing foils accompanying the germanium in the reactor [29].

The  $TeO_2$  crystals are produced by the Shanghai Quinhua Material Company (SQM) in Shanghai, China. Crystals produced by other organizations have proven to be inferior. A search of potential suppliers in the U.S. revealed that the only dealers found sold crystals produced by SQM or other companies outside of the U.S.

Long periods of operation suffer small excursions in temperature of the crystal array which deteriorates energy resolution. A stabilization technique proven to be successful in the MIBETA 20 crystal array experiment will be employed. A periodic injection is made of precisely known joule - power directly into the crystals through heavily doped meanders in  $Si$  chips glued to the surface [17].

The single tower of 40 crystals is presently under construction. It will be attached to the mixing chamber of the same dilution refrigerator (DR) used in the MIBETA experiment [17] and run as a test. It will also be run as an experiment called CUORICINO which is designed also to improve on the present sensitivity to  $\langle m_\nu \rangle$  obtained with isotopically enriched  $Ge$  detectors [7, 8]. By the time significant funding from this proposal could be spent on CUORE, CUORICINO will have proven the feasibility of the extension of the MIBETA technology to large arrays. This, plus the fact that CUORE requires no isotopic enrichment, puts CUORE well ahead of all the other options of a truly next generation  $0\nu\beta\beta$  experiments. The technology, novel though it is, is developed and to a large degree proven.

## 5 CONCLUSION

The CUORE array will have  $9.5 \times 10^{25}$  nuclei of  $^{130}Te$ . If the background is conservatively reduced to 0.01 counts /keV/kg/yr, then in one year of running, the sensitivity of CUORE would be  $Te_{1/2}^{0\nu} > 1.1 \times 10^{26}y$ . This corresponds to  $\langle m_\nu \rangle < 0.05eV$ . If eventually, the background would be reduced to 0.001 counts /keV/ kg/y, the sensitivity with one year of counting would be  $T_{1/2}^{0\nu} > 3.6 \times 10^{26}y$ , corresponding to  $\langle m_\nu \rangle < 0.03eV$ .

If in the two cases mentioned above, the detector was operated for a decade, the bounds on  $\langle m_\nu \rangle$  would be  $< 0.028eV$ , and  $< 0.017$  respectively.

If CUORE fulfills these expectations, it could be replicated by a factory 6 for a similar cost ( conservatively speaking ) as any of the experiments requiring isotopic enrichment.

The detector will also be used to search for cold dark matter (CDM). The



present thresholds of  $5\text{ keV}$  are equivalent to  $1.25\text{ keV}$  in ordinary  $Ge$  detectors, because ionization is 0.26 times as effective in converting nuclear recoil energy into a signal pulse as it is in converting photon energy. Such a large array could efficiently search for a seasonal variation in the CDM interaction rate. The large mass of  $Te$  theoretically enhances the interaction rate of many CDM candidates.

The CUORE crystals will be placed in known crystalline orientations which will allow a sensitive search for solar axions using the technique introduced by Creswick et al.[30], and demonstrated by the experiment of Avignone et al.[32].

It should also be recognized that the highly granular configuration of CUORE, equivalent to 10 layers of 100 crystal each, approximately forms a cube with 512 crystals in an inner cube with significant protection from a layer all around of 488 crystals. The coverage is not perfect because of necessary small spaces between crystals; however, it will significantly reduce background from gamma-rays coming from outside of the configuration.

Finally, while the main emphasis is on building an array of  $TeO_2$  crystals, CUORE, or the CUORE technique can accommodate any material that can be made into bolometers. The most promising competing experiments are the two large proposed  $^{76}Ge$  experiments GENIUS [15] and Majorana [30]. The direct observation of neutrinoless double beta decay absolutely requires at least two different experiments with different parent nuclei, if for no other reason than the uncertainties in nuclear matrix elements. In  $^{76}Ge$ , for example, this results in a factor of 4.3 in the value of  $\langle m_\nu \rangle$ , and a factor of 2.4 in the case of  $^{130}Te$ . These uncertainties should be carefully considered when comparing different proposals. For example, the present bounds on  $\langle m_\nu \rangle$  from  $^{76}Ge$  experiments range from 0.3 to 1.3 eV, while they range from 1.1 to 2.6 eV from the small MIBETA experiment recently completed [17]. CUORICINO should reach a comparable sensitivity during its test period. Which bound would be actually more restrictive? The answer lies in the uncertainties in the nuclear physics.

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